Optical Functional Performance of the Osteo-Odonto-Keratoprosthesis (OOKP)

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Keywords

Osteo-odonto-keratoprosthesis, OOKP, keratoprosthesis, KPro, visual function

Meeting Presentation

Aspects of this study were presented as an oral presentation at the 9th KPro Study Group Meeting 2014, Salzburg, Austria and as a poster at the Association for Research in Vision and Ophthalmology Annual Meeting 2012, Fort Lauderdale, USA.

Abstract

Purpose: To evaluate the optical and visual functional performance of the osteo-odonto keratoprosthesis (OOKP).

Methods: Optical design and analysis was performed with customized optical design software. Nine patients with implanted OOKP devices and nine age-matched control patients were assessed. Contrast sensitivity was assessed and glare effect was measured with a brightness acuity test (BAT). All OOKP patients underwent kinetic Goldmann perimetry and wavefront aberrometry and completed the National Eye Institute Visual Function Questionnaire-25 (NEI VFQ-25).

Results: Optical analysis showed that the optical cylinder is near diffraction-limited. A reduction in median visual acuity (logMAR) with increasing glare settings was observed from 0.04 (without glare) to 0.20 (with glare at 'High' setting) and significantly reduced statistically when compared to the control group at all levels of glare ($P < 0.05$). Contrast sensitivity was significantly reduced when compared to age-matched controls at medium and high spatial frequencies ($P < 0.05$). Median Goldmann perimetry was 65^{o} (interquartile range 64 - 74 ^{o}, V-4e isopters) and 69^{o} excluding two glaucomatous subjects. Several vision-related VFQ-25 sub-scales correlated significantly with visual acuity at various BAT levels and contrast sensitivity at medium spatial frequencies, including Dependency, General Vision, Near and Distance Activities.

Conclusions: The OOKP optical cylinder provides patients with a good level of visual acuity that is significantly reduced by glare. We have shown *in vivo* that updates to the optical cylinder design have improved the patient's field of view. Reduction of glare and refinement of cylinder alignment methods may further improve visual function and patient satisfaction.

Introduction

Osteo-odonto-keratoprosthesis (OOKP) is a technique / device first described by Strampelli in 1963 that utilises the patient's own canine tooth root and its surrounding alveolar bone to support a poly-methyl-methacrylate (PMMA) optical cylinder. [1-3] The OOKP is used in the treatment of corneal blindness in diseases with severe ocular inflammation and dry eye (such as end-stage Stevens-Johnson syndrome (SJS), ocular cicatricial pemphigoid, chemical burns, trachoma, dry eyes or multiple corneal graft failure) and has been shown to have good long term retention rates. [4-5] The technique has been previously described in more detail. [2]

OOKP surgery is unique in that the single optical cylinder replaces all of the optical elements of the eye. The optical power, originally provided by the cornea and lens, is replaced by the anterior and posterior surfaces of the PMMA cylinder. In addition, the pupil is essentially fixed and determined by the optical cylinder diameter since the iris has been removed (Fig. 1). The original Italian optical cylinders had a measured anterior cylinder diameter of 3.85mm and a posterior cylinder diameter of 4.09mm. These diameters combined with an overall length of just under 8mm contributed significantly to the measured visual field of 40^{o}. [5] Since then we have modified this design to maintain visual acuity and retention but increase the visual field by looking to increase in particular the posterior cylinder diameter. This is because the overall length and anterior cylinder diameter have more significant clinical constraints. [2] Minimal data are available about visual performance and optical properties of the OOKP. The aim of our study was therefore to assess the optical performance of the current generation OOKP device *in vivo* and assess its correlation with visual function reported subjectively by the patient. We aimed to identify sources for reduced optical performance so that we can further improve KPro design and improve patient satisfaction and visual performance.

Methods

Optical Analysis

Ray tracing analysis (Zemax optical design software, Radiant Zemax, WA, USA) was used to evaluate the field of view and axial image quality both in terms of Zernike aberration coefficients and Modulation Transfer Function (MTF). Prior to this analysis, the position of the image plane (retina) was optimised using through focus MTF curves, to produce peak image contrast at a spatial frequency of 30 cycles per degree (cpd), equivalent to 20/20. This was a surrogate for manifest refraction *in vivo.*

Light Scatter Measurement

Light scatter measurements were carried out using the set-up shown in Fig. 2 for a sample optical cylinder (Morcher GmbH) and a PMMA IOL (Rayner Intraocular Lenses Ltd., Hove, UK) for comparison. A 4mW He-Ne laser of wavelength 633nm (JD Uniphase, Mantaca, CA) was incident on an opal diffuser (Edmund Scientific, Barrington, NJ) to create a diffuse point source. The laser was translated to change the source eccentricity. The optical cylinder or IOL was mounted a maximum of 6cm behind the diffusing screen and a 4mm pinhole placed immediately in front of the IOL (the cylinder had a 4mm anterior surface diameter acting as its entrance pupil). A detector comprising a 1mm optical pinhole in front of a silicon photodiode (RS Components Ltd., Corby, UK) was mounted behind the optical cylinder/IOL. The photodiode was connected to a microameter (SP 043 microameter, Vinculum Products Ltd., Royston, UK). The change in illuminance in the pupil plane was measured by placing an illuminance meter (Pocket-Lux 2, LMT Lichtmesstechnik GmbH Berlin, Germany) with a 4mm aperture in the measurement plane whilst the laser was translated 19mm in 1mm increments giving a range of eccentricities up to approximately 17^{o}. For each position the illuminance was recorded and normalised to the peak reading. These values were used to correct for changes in illuminance by compensating for the non-Lambertian nature of the source. Measurements of the cylinder and IOL were carried out by first checking all components were aligned with the zero position of the laser. Next the diffuser was inserted and the detector translated in the x and z planes to maximise the detector output. Finally the laser was translated and microameter readings taken every mm giving a measure of irradiance in the detector plane due to light scatter for eccentricities up to approximately 17^{o}. This process was repeated six times for both the OOKP optical cylinder and IOL to assess repeatability.

Patients

The study was conducted in accordance with the tenets of the Declaration of Helsinki and with the approval from the Research and Development Directorate at Brighton and Sussex University Hospitals NHS Trust. Ethical approval was obtained from the Essex Research Ethics Committee (11/EE/0164). We reviewed the notes of all of the patients who had undergone OOKP surgery by one surgeon (CSCL). Our inclusion criteria were: Stable uncorrected visual acuity better than 20/60 for ten months or more after surgery and who had been assessed using previously published guidelines. [2] We recruited ten patients for this study. All patients were implanted with the UK design of the OOKP optical cylinder. Further details of the UK design of the cylinder have been previously published elsewhere. [2] Pre-operative diagnoses included Stevens-Johnson Syndrome (n=6), alkali chemical injury (n=1), graft versus host disease (n=1), linear IgA disease (n=1) and LOGIC syndrome (n=1). No patients had bilateral surgery with the other eye visual acuity being worse than Count Fingers in all subjects. Two patients with glaucoma were not excluded because glaucoma is a common post-operative complication following OOKP surgery, with a reported incidence of up to 47%. [4] One patient developed exposure in one corner of the buccal mucosa that underwent successful repair and was not excluded. One patient was excluded following recruitment due to poor co-operation with the instructions.

Patient ages ranged from 21.9 to 67.6 years (mean: 49.7 ± 13.2 years). Nine healthy age-matched (P = 0.95) controls (mean: 50.1 ± 11.8 years) were recruited from the hospital clinic. All patients underwent visual acuity measurement with glare sensitivity testing and contrast sensitivity assessment and patients were asked to complete the National Eye Institute visual function questionnaire (NEI VFQ-25). OOKP patients also performed kinetic Goldmann perimetry and wavefront aberrometry.

Visual Performance

Visual acuity (VA) was measured using an ETDRS chart (Precision Vision, IL, USA) from a distance of four metres. Glare sensitivity was measured with a brightness acuity tester (BAT; Mentor O&O, MA, USA). Visual acuity measurements were repeated under the three BAT glare levels (Low, Medium and High). Visual acuity was converted to the absolute value of the logarithm of the minimum angle of resolution (logMAR). Our motivation for using the Brightness Acuity Tester to assess the effect of glare will be given in the Discussion.

Contrast sensitivity (CS) was assessed using Metropsis Visual Stimulus Generation software (Cambridge Research Systems Ltd, Rochester, UK) at 0.3, 0.7, 2.20, 3.50, 10.4 and 14.5 cpd. Kinetic Goldmann perimetry using a V-4e stimulus (Haag-Streit AG, Bern, Switzerland). VA, glare sensitivity, CS and kinetic perimetry were performed with refractive correction as required. Wavefront aberrometry was performed using a Nidek OPD-scan (Nidek, Aichi, Japan).

Visual Function questionnaire

The NEI VFQ-25 was completed by the OOKP patients and the control group. Subscales include: general health, general vision, ocular pain, near activities, distance activities, social functioning, mental health, role difficulties, dependency, colour vision and peripheral vision. We ignored the vehicle-driving subscale as our patients would not be eligible to drive. Each subscale is scored between 0 (the activity is so difficult the patient had to stop it) to 100 (no difficulty at all).

Statistical Analysis

Dues to the low numbers (n=9) in each group we used non-parametric statistics throughout. Data are given as median and interquartile ranges (IQR) The Mann-Whitney U test was used to compare VA, CS measurements and VFQ-25 scores in patients and controls. Spearman's rank correlation coefficient rho was used to look for relationships between visual function measurements (VA, CS) and VFQ scores in OOKP patients. The level of statistical significance was taken as $P < 0.05$. All analyses were conducted using IBM SPSS Statistics for Macintosh, Version 20.0 (Armonk, NY: IBM Corp.).

Results

Optical Analysis

The optical cylinder is near diffraction-limited (Fig. 3). The theoretical field of view was found to be 72^{o} (Fig. 4). Ray trace analysis demonstrated a Root Mean Square (RMS) wavefront error of 0.04µ which is the same as the total spherical aberration since the cylinder is considered a rotationally symmetric system with no other terms present. The change in image quality up to a 40^{o} semi-field angle is illustrated with spot diagrams (Fig. 5). These diagrams show the intersection of a regular polar grid of rays with the image plane. They give an indication of the retinal illuminance, which is important in visual field testing since the increment threshold must be reached for the stimulus to be detected. When combined with Fig. 3, they also demonstrate significant vignetting caused by the length of the optical cylinder.

Light Scatter Measurements

Light scatter function measurements out to 17^{o} eccentricity show a marked increase for the OOKP optical cylinder compared to the reference IOL (Fig. 6). Measurements were highly repeatable. The area under the scatter function, which correlates with the amount of light scattered, is a factor of 1.58x higher for the OOKP optical cylinder and readings in the periphery of the light scatter function are, on average, a factor of 10x higher for the OOKP cylinder. The small secondary peak for both measurements at approximately 10^{o} eccentricity occurs due to a secondary weaker ring of illumination created by the diffuser and is of no significance since it is a systematic measurement error for both samples. However the larger secondary peak at 5.5^{o} eccentricity for the IOL is due to the IOL and/or its mount since it also occurred when a ground glass diffuser was used and is not seen in the scatter function for the OOKP optical cylinder.

Visual Performance

Median (IQR) logMAR VA observed in OOKP patients reduced with increasing BAT glare levels, from 0.04 (-0.08 – 0.44) with no glare, 0.04 (-0.08 – 0.62) with low glare, to 0.20 (-0.08 – 0.62) with medium glare and 0.20 (-0.06 – 0.62) with high glare (Table 1). No such changes were seen in controls from 0.00 (-0.10 – 0.12) with no glare to 0.02 (-0.10 – 0.12) with high glare. These differences in logMAR VA values between patients and controls were statistically significant at low, medium and high glare levels (P = 0.040, 0.008 and 0.003, respectively), but not so when there was no glare (P = 0.063).

Contrast sensitivity was reduced in OOKP patients when compared to age-matched controls at medium (2.2 and 3.5 cpd; P = 0.031 and 0.015, respectively) and high (10.4 and 14.5 cpd; P = 0.005 and 0.009, respectively) spatial frequencies, but not at low (0.3 and 0.7 cpd; P = 0.536 and 0.171, respectively) spatial frequencies (Table 2).

Kinetic Goldmann

The median V-4e isopters measured for all patients using Goldmann perimetry was 65^{o} (IQR 49-74^{o}). Two patients had glaucoma, one had a visual field of 24^{o} and another with both glaucoma and retroprosthetic membrane (RPM) formation had a visual field of 34^{o}. The median field in the seven remaining patients without glaucoma was 69^{o} (64 - 74^{o}).

Wavefront Aberrometry

Measured values of aberrations were higher than expected from the theoretical performance (Table 3). Ray trace analysis calculates a RMS wavefront error of 0.04μ whereas in our patients the median RMS error was 5.95μ (IQR 5.18 – 13.29 μ). Significant aberrations were observed for tilt (2.57μ), coma (1.65μ) and trefoil (1.70μ) terms.

Visual Function questionnaire

Measured values of visual function score are given in Table 2. Our median (IQR) composite score was 77 (IQR 55 – 86) in our OOKP group and was significantly different when compared to the composite score of 97 (93 - 98) in our control group (P = 0.001).

VFQ-25 subscale performance was statistically different between OOKP patients and the control group in most subscales except general vision, ocular pain or colour vision. These differences were most marked for distance, social functioning, role difficulties and peripheral vision subscales (Table 4).

Several visual function subscales correlated with visual function measurements in our OOKP patients. VA for various BAT glare levels were found to be statistically significantly and inversely correlated with general vision, near activities and distance activities (r = -0.70 to -0.86; all $P < 0.05$). Additionally, dependency correlated statistically significantly with BAT glare levels at medium (r = -0.79, P = 0.011) and high (r = -0.74, P = 0.022).

Contrast Sensitivity at primarily at the two medium spatial frequencies (2.2 cpd and 3.5 cpd) was found to be statistically significantly correlated with general vision, near activities and distance activities as well as dependency (r = 0.67 to 0.83; all $P < 0.05$).

Discussion

The single-piece optical cylinder has a vital role to play in the visual rehabilitation of OOKP patients. Present designs for use in OOKP surgery involve a single piece of clinical quality PMMA, manufactured by lathe cutting and tumble polishing, supported by an autologous tooth root and alveolar bone. [2] One reason for this apparently simple design is because the optical cylinder and its support form part of a complex multistage operation and hence a further increase in complexity in cylinder design needs to be evidence-based and that is the purpose of our study. We also wanted to evaluate the in vivo results with the updated optical cylinder design.

Visual function can be affected by any aspect of the OOKP optical cylinder. The anterior aspect of the cylinder is exposed and may develop scratches which could result in surface light scattering and reduced visual function. However PMMA used in the optical cylinder is long established as an intraocular material and minimal signs of wear or scratching have been demonstrated in the Italian cohort of patients after 20–30 years follow-up.

We found good levels of visual acuity in our OOKP patients that are comparable to age matched controls at no glare and low glare levels. Sayegh et al. observed that the change in visual acuity in patients implanted with a Boston type 2 KPro was decreased in an Afro-Caribbean patient presumed to be because the darker skin pigment served as better protection from glare from the surrounding cornea. [6] We did not observe this effect in our two patients of Asian and Afro-Caribbean descent.

We found that contrast sensitivity was significantly reduced at medium and high spatial frequencies but not at low spatial frequencies when compared to age-matched controls. This could be caused by higher-order aberrations in the optics of the OOKP. The OOKP optical cylinder is a rotationally symmetric system and so theoretically spherical aberration is the only higher-order aberration present. Measurements *in vivo* however revealed higher-order aberrations with a significantly greater RMS value compared to theoretical predictions. This data was also significantly greater than population norms and could represent data from outliers. Of this data however the dominant aberrations were tilt, coma and trefoil. Although tilt has been shown in previous studies to be the least significant factor affecting higher-order aberrations, it has been shown to be associated with coma aberrations, a finding that is also suggested with our results. [7] Therefore, given the low theoretical levels of aberrations with the OOKP cylinder, we would not expect changes to the cylinder design itself to affect the results. Instead it is more likely that other factors such as tilt and inability to target refractive error would affect visual function given the complexity of the surgery.

Applegate et al. have reported that some higher-order aberrations such as coma play a greater role in affecting vision than others. [8] Refractive error and decentration also play a role in affecting higher-order aberrations and therefore surgical technique is crucial in these patients in order to improve visual function. However, we found a poor correlation between clinically observed tilting of the optical cylinder and measured tilt aberration. Patients with significant tilt of their optical cylinder on clinical examination did not have significant tilt aberrations on wavefront aberrometry. Similarly, some patients who were not noted to have tilted optical cylinders were found to have significant tilt aberration on wavefront analysis. It is possible that the aberrometer produces less reliable results for a fixed pupil size of 4mm due to lower light levels. Whatever the cause, further studies are necessary to develop software to predict changes in optical performance with tilt or decentration and to assess the effect of clinically significant tilt in OOKP patients.

Our visual field results with our cohort of patients are similar to those obtained by the Singapore OOKP study group. [9] The median visual field in our patients was 65^{o} (69^{o} if the patients with glaucoma was excluded) which is greater than reported fields of 40^{o} with the original Italian design confirming that modifications to the cylinder have helped to improve patient's visual field. Previous it has been shown that the Italian cylinder has a maximum theoretical visual field of 76^{o} and further modifications can increase this to a maximum of 90^{o}. [10] Increasing the diameter of the cylinder will help to improve the visual field but this is limited by the diameter of the available root of the tooth. However, if the cylinder diameter is too large then visual function may be affected by glare. [11] Development of a synthetic OOKP analogue to replace the tooth may reduce this limitation and therefore allow for a larger cylinder diameter that is not affected by glare. [2] The current UK design for the OOKP optical cylinder is longer and wider than the Italian cylinder. [2] Like the Italian cylinder, the current Brighton OOKP cylinder visual field does not match the measured theoretical visual field. This could be due to decentration of the optical cylinder or reflection from the side wall causing glare. [11]

Glare is a commonly reported symptom following OOKP surgery and has also been observed with other KPro surgery such as the Boston KPro. [6] The decline in visual acuity with increasing glare settings was similar to those reported with the Boston type 2 KPro. Glare could be a result of the surrounding cornea, the anterior surface, the wall or the posterior surface of the OOKP cylinder. Sayegh et al. has demonstrated that glare causes a much greater decrease in visual acuity with the Boston Type 1 KPro compared with the Type 2 KPro where there is more corneal exposure to external light sources and that this is reduced if a black contact lens is used to cover the exposed surrounding cornea. [6] As the buccal mucous membrane overlies the OOKP and cornea, we would expect the effect of glare from transillumination of the surrounding cornea to be minimal.

The use of the Brightness Acuity Tester (BAT) is worthy of note because it has been established for some time that glare tests similar to the BAT do not provide a measure of forward light scatter and hence glare because they confound the optical and neural changes that take place.[12,13] Specifically it has been reported that in some subjects introduction of a glare source can improve visual acuity most likely because the improvement in acuity from changes in retinal sensitivity outweigh the reduced contrast caused by the forward light scatter.[13] However, the BAT does produce a measure of visual acuity in the presence of glare that has a relevance to real world situations where eyes are subject to both straylight and retinal sensitivity changes. We have not attempted to measure glare directly but rather the effect of glare on visual performance given that we have additionally made in vitro measurements of forward light scatter on the optical cylinders. The BAT was also used by Sayegh et al. and hence we can directly compare results between the two studies on what are the two keratprosthesis devices with the best survival rates for end-stage corneal disease.[6]

Light reflection from the wall of the cylinder could act as a source of glare resulting in a reduction of visual acuity and visual field.[14] Hille et al. has shown for their cohort of patients using an optical cylinder of 3mm diameter that the measured visual field was significantly less than the theoretical visual field and suggested this was due to the reflection of light from the walls of the cylinder resulting in a reduction of vision.[11] It has been demonstrated that treating the cylinder wall may reduce this effect, Sokol et al. having painted the wall of a KPro optical cylinder black and Sayegh et al. demonstrating a similar effect with the Boston KPro optical cylinder on computer simulations, assuming the inner surface of the cylinder acts like a mirror.[6, 15] However, they also suggested that the contribution to total glare from light reflected from the wall of the cylinder was minimal. As the OOKP optical cylinder has a longer tubular wall, the effect of glare in an OOKP eye may be greater than that with the Boston KPro. We suggest that the fixed diameter of the optical cylinder may also play a role in glare sensitivity. Reducing optical cylinder diameter (the entrance pupil of the optical system) reduces the light entering from different field angles which although detrimental to the visual field, will reduce the effect of aberrations and glare and therefore improve image quality.

RPM is the formation of an opaque membrane on the posterior aspect of the optical cylinder of unknown aetiology and is a frequent complication occurring in 0-20% of OOKP study populations. [4] Our current cylinder design has a longer posterior section length than the Italian design (2.75mm compared to 2.25mm on the original Italian design) and this helps to counter RPM formation. The optical design principle is to have approximately equal (but opposite in sign) curvatures on the anterior and posterior surfaces. This provides control of spherical aberration while maintaining reasonable off-axis image quality as assessed by computer ray tracing simulation. The radii of curvatures vary from approximately ±11mm to ±14mm depending on the required back vertex power. The increased posterior section length of 2.75mm ensures that the edge of the posterior surface is far enough away from the dentine host to reduce RPM formation even with this range of curvatures. One of our patients was observed to have a degree of RPM formation causing significant glare reduction in vision and we were unable to obtain aberrometry readings in this patient. RPM can be managed with Nd:YAG laser membranotomy but the procedure often needs to be repeated. There is also a risk that the posterior face of the cylinder can be damaged and sometimes surgical intervention may be required if the RPM is too thick. Therefore further design elements may need to be considered in order to reduce the risk of RPM formation and resulting loss of visual function.

Visual function, assessed by VFQ-25, was statistically worse in our OOKP patients than the control group and was markedly so for certain subscales such as peripheral vision ($P < 0.0001$). There did not seem to be any significant correlation between peripheral vision and glare or contrast sensitivity. The NEI VFQ-25 has been shown to have good correlation with other visual function questionnaires such as the Visual Activities Questionnaire (VAQ), but only one of the questions relates to peripheral vision function and therefore there is scope for bias if relying on just the NEI VFQ-25 to assess patient perception of their peripheral vision. [16]

Visual function was generally comparable to other eye studies assessing visual function in certain subscales. [17-19] Studies have however suggested that glare contributes to reduced contrast sensitivity and that this will play a role in affecting visual function. [20] Our results would agree with these studies having found statistically significant correlation between glare and visual function amongst our patients, with dependency function being statistically correlated with medium and high glare settings.

Conclusions

Visual acuity is reduced by glare and patients experienced a lower contrast sensitivity compared to age-matched controls. The NEI VFQ-25 correlated significantly with visual acuity at different glare levels and with contrast sensitivity at medium spatial frequencies. Further enhancements in optical performance software and cylinder design, notably the reduction of glare and alignment of the cylinder, could further improve visual function. These developments can be tested using the objective measures used in this study now we have for the first time shown that they correlate with visual function in vivo.

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Figure Legend

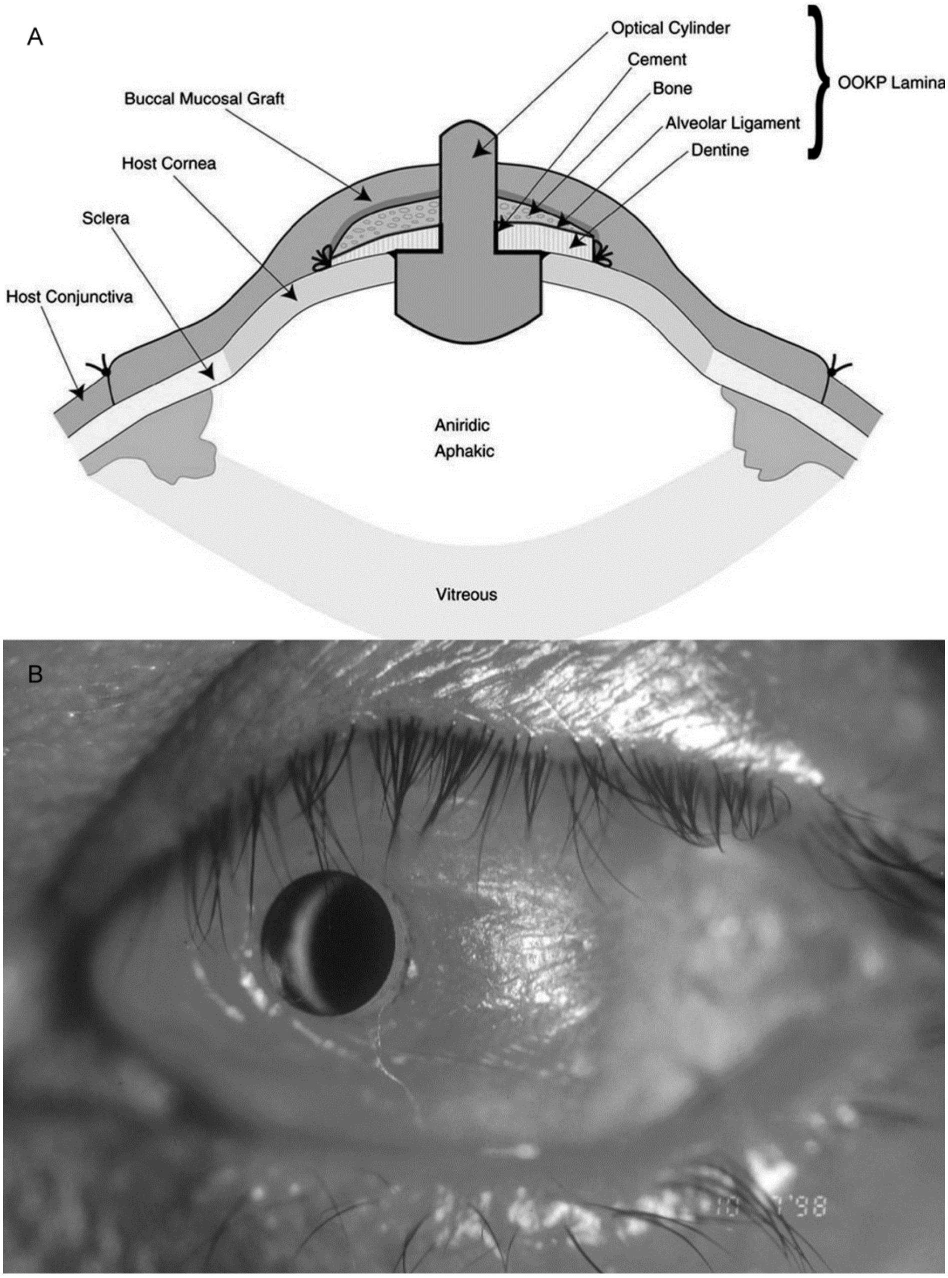

Figure 1: A) Schematic diagram of cross section anatomy of an OOKP eye. B) External appearance of an OOKP eye.

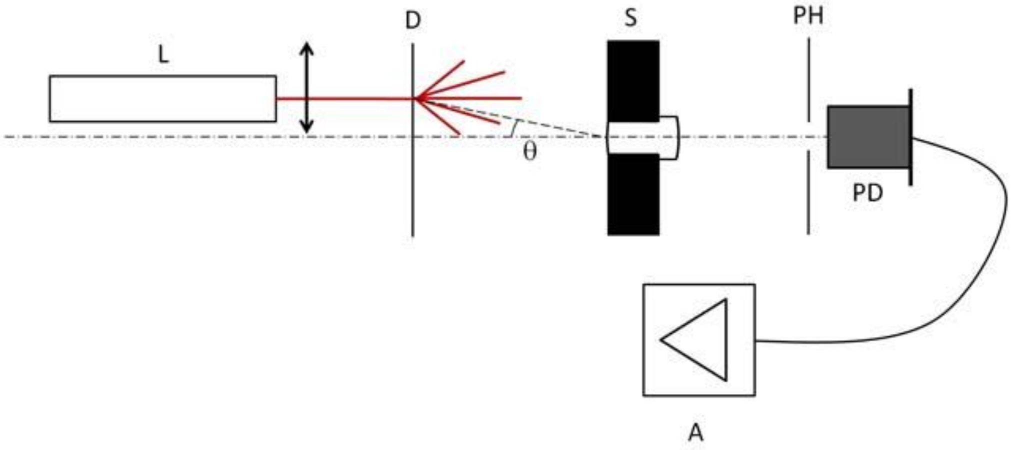

Figure 2: Optical set-up for light scatter function measurements of the OOKP optical cylinder and a reference IOL; L, He-Ne laser (633nm); D, diffuser; S, sample; PH, pinhole; PD, photodetector and A amplifier.

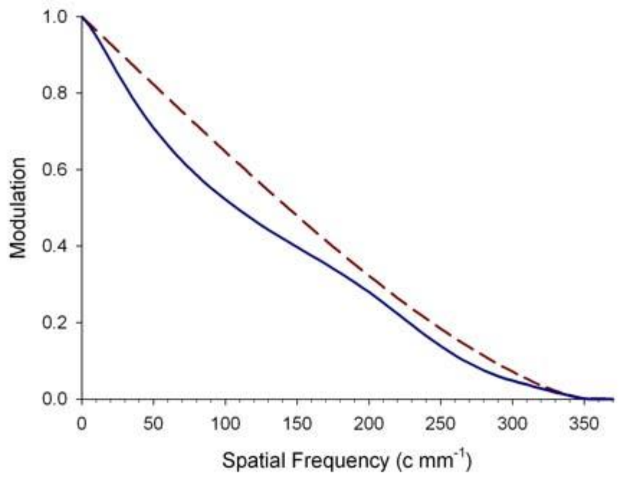

Figure 3: Calculated monochromatic (λ = 550nm) Modulation Transfer Function (solid curve) for axial performance showing the optical cylinder to be near diffraction-limited (dashed curve).

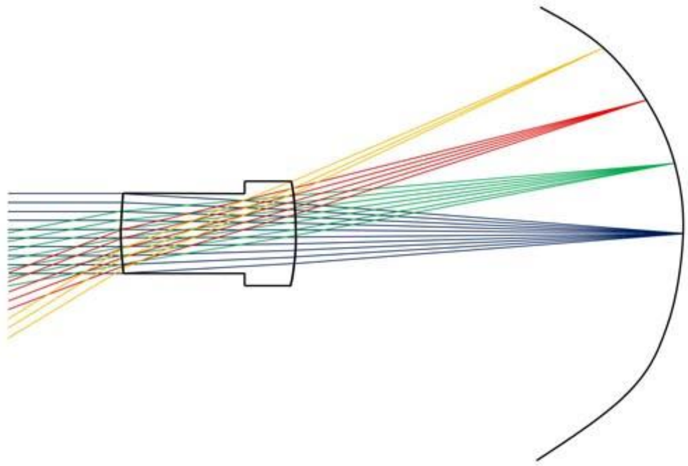

Figure 4: Optical cross-section showing the passage of rays through the cylinder and corresponding spot diagrams for semi-field angles of 0, 10, 20 and 30 degrees.

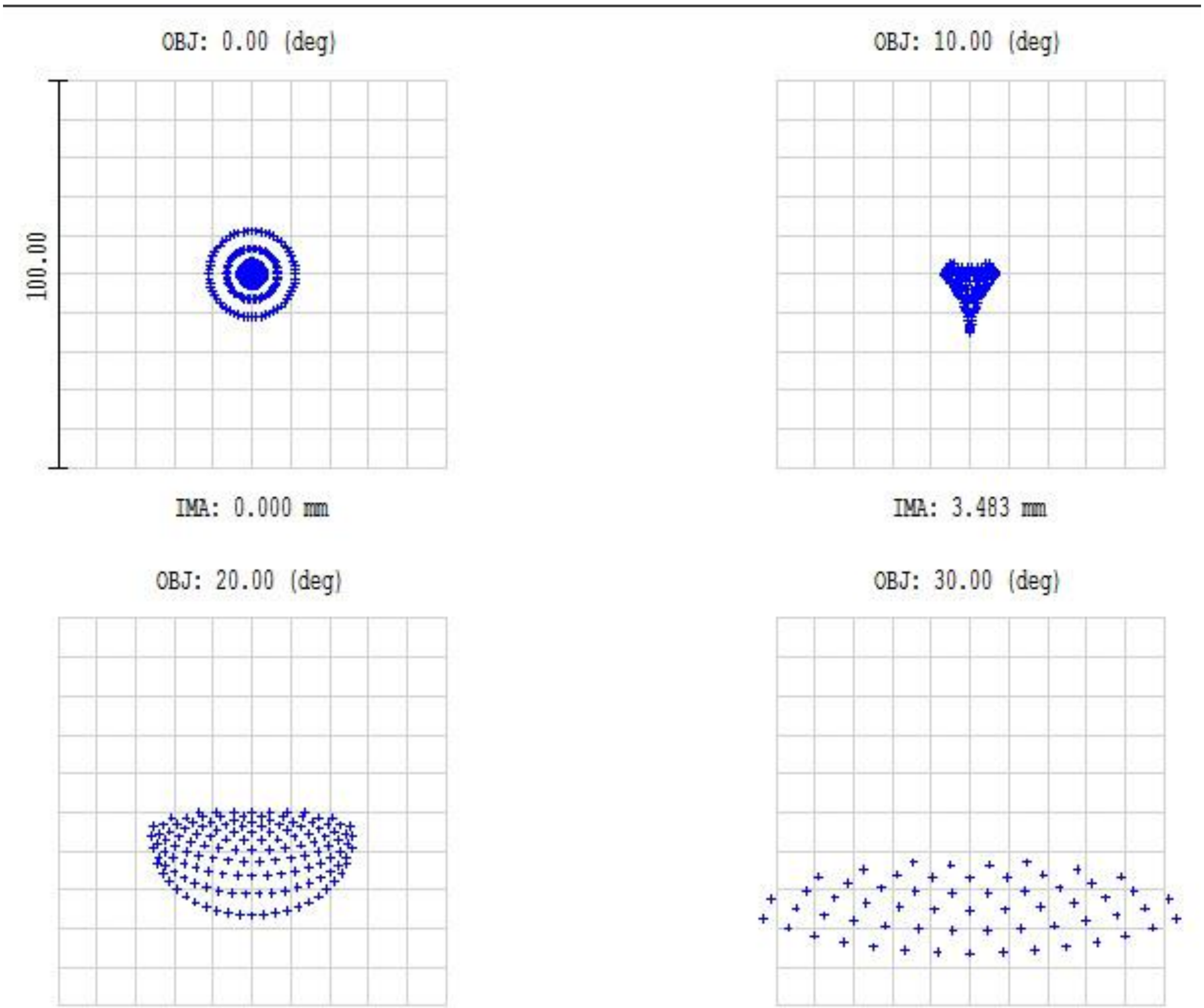

Figure 5: Spot diagrams showing the ray density in the image plane for field angles of 0, 10, 20 and 30 degrees

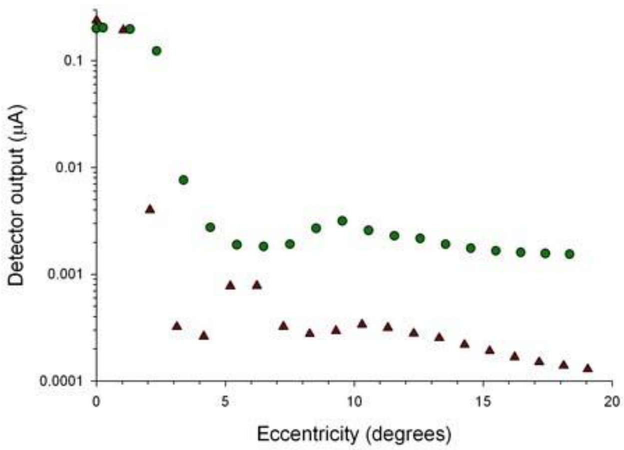

Figure 6: Light scatter function measurements (measured in μA) for an OOKP optical cylinder (circles) and a PMMA IOL (triangles) for comparison (error bars too small to indicate).

Tables

logMAR VA at different glare levels	**OOKP group (n = 9)**	**Control group (n = 9)**	**p**
No Glare	**0.04** (-0.08 – 0.44)	**0.00** (-0.10 – 0.12)	0.063
Low	**0.04** (-0.08 – 0.62)	**0.00** (-0.10 – 0.12)	0.040
Med	**0.20** (-0.08 – 0.62)	**0.00** (-0.10 – 0.12)	0.008
High	**0.20** (-0.06 – 0.62)	**0.02** (-0.10 – 0.12)	0.003

Table 1: logMAR VA Scores (Median ± Interquartile range, IQR) for OOKP patients and Controls. P value is from Mann Whitney U test

Spatial Frequencies (Cycles per degrees, cpd)	**OOKP group (n = 9)**	**Control group (n = 9)**	**p**
0.3 cpd	**1.6** (1.2 – 2.0)	**1.6** (1.4 – 1.7)	0.536
0.7 cpd	**1.7** (1.6 – 2.2)	**1.9** (1.8 – 2.2)	0.171
2.2 cpd	**2.0** (1.6 – 2.4)	**2.3** (2.0 – 2.7)	0.031
3.5 cpd	**1.9** (1.1 – 2.6)	**2.5** (1.4 – 2.9)	0.015
10.4 cpd	**0.8** (0.4 – 1.4)	**1.8** (0.7 – 2.0)	0.005
14.5 cpd	**0.7** (0.5 – 1.4)	**1.1** (0.6 – 1.5)	0.009

Table 2: Contrast Sensitivities (Median ± Interquartile range, IQR) of various spatial frequencies for OOKP patients and Controls. P value is from Mann Whitney U test

Term	Median (microns)	Interquartile range
Root Mean Square Total	5.95	5.18 – 13.29
Σ Tilt	2.57	1.76 – 5.24
Σ Coma	1.65	1.27 – 2.44
Σ Trefoil	1.70	0.60 – 4.77
Σ Quadrefoil	0.17	0.03 – 3.50
Σ Spherical	1.08	0.35 – 1.73
Σ Astigmatism	1.13	0.60 – 1.96

Table 3: Zernike aberration coefficients collected by term and overall from Nidek OPD-Scan (Nidek, Aichi, Japan)

	OOKP group (n = 9)	**Control group (n = 9)**	**p**
Overall score	***77** (55 – 86)*	***97** (93 – 98)*	*0.001*
Subscales			
General health	**50** (36 – 77)	**78** (69 – 95)	0.040
General vision	**80** (55 – 100)	**95** (85 – 100)	0.202
Ocular pain	**88** (50 – 100)	**100** (69 – 100)	0.329
Near activities	**88** (58 – 98)	**100** (96 – 100)	0.023
Distance activities	**67** (50 – 77)	**100** (98 – 100)	< 0.0001
Social functioning	**83** (56 – 92)	**100** (-)	< 0.0001
Mental health	**80** (33 – 90)	**95** (93 – 100)	0.007
Role difficulties	**75** (38 – 88)	**100** (-)	< 0.0001
Dependency	**81** (25 – 75)	**100** (-)	0.004
Colour vision	**100** (75 – 100)	**100** (-)	0.066
Peripheral Vision	**50** (25 – 75)	**100** (-)	< 0.0001

Table 4: National Eye Institute Visual Function Questionnaire (NEI VFQ-25) scores for OOKP patients and controls. Data are given as medians and interquartile ranges; in some cases IQR cannot be calculated as all controls had maximum scores of 100. p-values given for Mann-Whitney U test.